ELECTRA: A REPETITIVELY PULSED, ELECTRON BEAM PUMPED KrF LASER TO DEVELOP THE TECHNOLOGIES FOR FUSION ENERGY*

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Abstract

The Electra Krypton Fluoride (KrF) Laser program is developing the science and technology needed for inertial fusion energy (IFE). The Electra main amplifier is pumped by two 500 kV, 100 kA, 140 nsec, electron beams. The pulsed power system can run continuously at 5 Hz for 100,000 shots . Electra has produced 700 J of laser energy per pulse in 1 Hz and 5 Hz bursts, and 300 Joules for 10,000 shots at 1 Hz (about 2.8 hrs). Recent advances include: a) a new "ceramic honeycomb cathode" that improves the e-beam rise time and uniformity, b) experiments and supporting simulations to efficiently pass the e-beam the vacuum window (hibachi foil) and into the laser gas, and c) first e-beam tests of the smaller "Pre-Amplifier" Laser (175 kV, 85 kA, 40 nsec) that will provide the laser input to the main amplifier. Electra is close to meeting its goals: We have demonstrated a new laser gated and pumped thyristor which will be the basis for a durable and efficient pulsed power system. The front end will demonstrate this architecture. The overall laser efficiency (wall plug to light on target) is predicted to be > 7%, based on advances in the individual components. The major remaining challenge is to realize a long lived hibachi foil at the higher (5 Hz) rep rate. We believe this to be an issue of thermal management, and several methods of cooling the foil are under evaluation.

I. INTRODUCTION

There is a large US program underway to develop a practical fusion power source based on lasers, direct drive targets, and solid wall chambers [1]. In this approach an array of high-energy laser beams symmetrically and directly illuminates a cryogenic target that has been injected into a chamber. The target is a spherical shell 4 mm in diameter and 0.4 mm thick, containing deuterium and tritium, . The lasers compress the shell to such high densities (40 x solid) that a localized hot spot in the center undergoes thermonuclear ignition. The resulting thermonuclear burn wave propagates outward releasing energy, which is converted to generate electricity. The attractiveness of the approach discussed here lies in its inherent simplicity, its separable architecture, and the modular nature of the laser driver. This lowers development costs and allows multiple options for the lasers, targets, and chambers. This paper gives an overview of the Electra program at NRL, which is developing the science and technologies for a krypton fluoride (KrF) laser that can meet the requirements for fusion energy. The development of the other components needed for Laser Fusion Energy (e.g. targets, final optics, chambers, etc.) can be found in the references [1].

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14. ABSTRACT
The Electra Krypton Fluoride (KrF) Laser program is developing the science and technology needed for inertial fusion energy (IFE). The Electra main amplifier is pumped by two 500 kV, 100 kA, 140 nsec, electron beams. The pulsed power system can run continuously at 5 Hz for 100,000 shots . Electra has produced 700 J of laser energy per pulse in 1 Hz and 5 Hz bursts, and 300 Joules for 10,000 shots at 1 Hz (about 2.8 hrs). Recent advances include: a) a new ceramic honeycomb cathode that improves the e-beam rise time and uniformity, b) experiments and supporting simulations to efficiently pass the e-beam the vacuum window (hibachi foil) and into the laser gas, and c) first e-beam tests of the smaller Pre- Amplifier Laser (175 kV, 85 kA, 40 nsec) that will provide the laser input to the main amplifier. Electra is close to meeting its goals: We have demonstrated a new laser gated and pumped thyristor which will be the basis for a durable and efficient pulsed power system. The front end will demonstrate this architecture. The overall laser efficiency (wall plug to light on target) is predicted to be > 7%, based on advances in the individual components. The major remaining challenge is to realize a long lived hibachi foil at the higher (5 Hz) rep rate. We believe this to be an issue of thermal management, and several methods of cooling the foil are under evaluation.

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Electron beam pumped KrF lasers are an attractive approach for a fusion driver because they have very high beam spatial uniformity, which reduces the seed for hydrodynamic instabilities; they have a short wavelength (248 nm) that increases the rocket efficiency and raises the threshold for deleterious laser-plasma instabilities; they have the capability for "zooming", (decreasing the spot size to follow an imploding pellet and thereby increasing the coupling efficiency); and they are based on an inherently robust and relatively inexpensive pulsed power technology. The main issues that need to be addressed are efficiency and durability.

These issues are being addressed with the Electra laser [2], a 400-700 J repetitively pulsed laser system. The Electra laser main amplifier is shown in Figure 1.

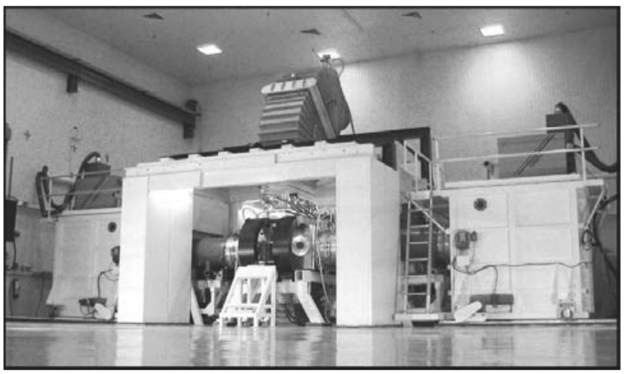

Figure 1. The Electra Main Amplifier

Although this paper concentrates on the fusion application, the electron beam/ gas laser technology described here is appropriate for other applications as well. Other wavelengths can be accessed by changing the laser gas. Lasing has been demonstrated in Argon-Xenon at 1.733 μm [3,4], XeF at 351 nm, and others [5].

II. KrF LASER BASICS

KrF is an excimer (<u>Exc</u>ited Di<u>mer</u>) laser based on a molecular electronic transition to a ground state which immediately dissociates. The process is as follows: Energy + ($Kr + F_2$) $\Rightarrow$ $KrF^* + F$ $\Rightarrow$ $Kr + 2F + h\nu$ (λ = 248 nm), where 248 nm is the fundamental wavelength. The transition from the bound upper level to the strongly repulsive ground state results in a very large bandwidth, typically on the order of 1-3 THz. Large KrF lasers, such as the size required for a fusion driver (10 J to 10's of kJ, pulses of 20-1000 nsec) are pumped with electron beams. The concept is shown schematically in Figure 2.

The electron beams are emitted from a field emission cathode driven by a fast pulsed power system. The electron beam propagates through a thin foil, which serves as the anode, and into the laser gas. The foil physically

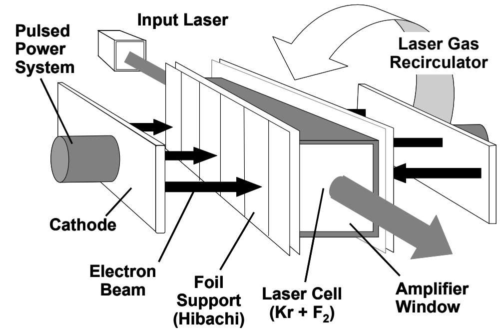

Figure 2. Components of a KrF Laser Amplifier.

separates the diode region, which is at vacuum, from the laser cell, which is at atmospheric pressure or above. The structure that supports the foil is known as a hibachi. Typically two electron beams are injected into the laser cell from opposite sides. The laser axis is perpendicular to the electron beam propagation. The beam voltage and laser gas pressure are adjusted to give a flat deposition profile across the laser cell, in order to produce a spatially uniform laser profile. In a repetitively pulsed system a recirculator is needed to cool and quiet the laser gas between shots. An external magnetic field prevents the electron beam from pinching as it propagates into the laser cell. Large, single shot amplifiers have also been built without a magnetic field [6,7]. In those systems smaller diodes are arranged cylindrically about the laser cell. However the magnetically guided systems have proven to be more efficient and are more compatible with the gas recirculator needed for repetitive operation.

The electron beam parameters are chosen to optimize the electron beam energy deposited into the laser gas, whose composition and pressure have been adjusted to maximize the laser output energy. The electron beam energy should be at least 500 keV, in order to minimize losses in the hibachi foil. The laser gas pressure should be around an atmosphere with as little Kr as possible, in order to maximize the laser efficiency. The electron beam power deposited in the gas (known as the pump power) needs to be 400 - 800 kW/cc, for laser efficiency considerations. The practical size of available laser output windows leads to laser cell dimensions in the direction of the electron beam propagation to be 30-100 cm. The requirement to stop the electron beam in these distances at optimal gas pressures sets the voltage between 500 and 800 keV. The pump power requirements fix the current to between 100-200 kA. The pulse length is determined by the total energy desired from the system, but there is a practical limit of around 500- 600 nsec that arises from balancing the conditions for an efficient laser, the requirement to have the total laser output energy below the laser fluence damage threshold on the output window,

and maintaining a flat diode impedance during the pulse. In addition to the above constraints, it is important that the voltage should rise and fall as rapidly as possible. There are two reasons for this: 1) The voltage is lower during the rise and fall, the energy deposition is skewed towards the foils, leading to a non-uniform laser beam profile, and 2) the hibachi foil stops more electrons at lower voltages, hence compromising the system efficiency. All of these constraints suggest that the best way to produce the electron beam is with a pulsed power system that produces a fast rise, a fast fall, and a flat top power pulse. Further considerations are discussed reference [2].

III. PROGRESS IN ELECTRON BEAM PUMPED KrF LASER DEVELOPMENT

In a fusion energy system the laser would consist of a series of identical beam lines. Thus it would be only necessary to develop one beam line in order to know how to build the entire laser system. For example, in one topology under consideration there would be 60 beam lines with each beam line producing 40 kJ to produce a 2.4 MJ laser. We believe that the technology for electron beam pumped gas lasers is sufficiently mature that it would require relatively modest development to build a system of this size that could fire on a single shot basis and meet the target physics requirements [8,9,10]. The main challenge is to build one that is repetitively pulsed and can meet the fusion energy requirements for durability, efficiency and cost. Based on power plant studies [11], the laser should meet the requirements shown in Table I. Note the first two are already met by a KrF laser [12] . In Table 1, durability is defined as the number of shots between major maintenance (2 years at 5 Hz)

Table I: Requirements for an IFE Laser Driver

Parameter	Requirement
Beam quality (high mode)	0.2%
Optical bandwidth	3 THz
Beam power balance	2%
System efficiency	6-7%
Rep-Rate	~ 5 Hz
Durability (shots)	3×10^8
Lifetime (shots)	10^{10}
Cost of entire laser	\$400/J
Cost of pulsed power	\$10/J(e-beam)

This section describes our research and development to meet the efficiency, rep-rate and durability specifications. It is organized along the components shown in Figure 2.

A. Pulsed Power- First Generation System [2,13]

The main amplifier for Electra is pumped by two counterstreaming 500 kV, 100 kA, 100 nsec. 30 cm x 100 cm electron beams. Each is driven by its own pulsed powers system that consists of an 86 kV capacitor bank that pulse charges two parallel water lines through a 12:1 step up transformer. The lines are then discharged through an SF_6 insulated, laser triggered spark gap. The system can run continuously for 100,000 shots. The duration of the continuous runs are limited by erosion of the Elkonite output switch electrodes. Replacing these takes less than two hours. This First Generation System has proven to be more than sufficient to develop the laser components (cathode, hibachi, KrF physics).

B. Pulsed Power- Next Generation System

A more advanced pulsed power system is required to meet the fusion energy requirements for durability, efficiency and cost. The path to durability is best realized by incorporating all solid state switching components, whereas efficiency. The path to low cost and efficiency requires minimizing the number of pulsed power compression stages. The latter requires that the switch in the primary energy storage stage be as fast as possible. We have developed a design for an all solid state, single stage pulse compression generator that is projected to have a wall-plug to e-beam flat-top efficiency of 87%, and a cost of \$8.45/Joule. The prime store is an ultra fast (~1.6 μsec) Marx generator, which, as shown in Figure 3, will pulse charge a water insulated PFL. At peak charge, the energy in the PFL is transferred by a magnetic switch into transit time isolator (TTI) and then into the electron beam load. The TTI is a pulse line of the same length, geometry and construction as the PFL, and serves to minimize the voltage rise time. We estimate the overall efficiency of this system from wall plug to flat top e-beam, is > 85%

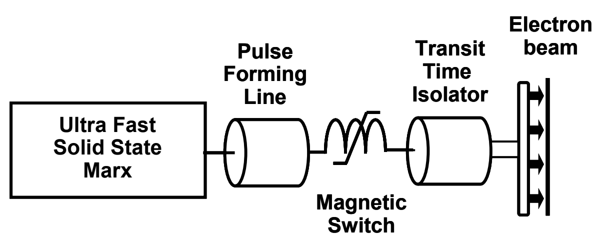

Figure 3: Advanced Pulsed Power Architecture

The principal behind the magnetic switch is well established [14]. An inductor is placed between the center conductors of the PFL and TTI, and is adjusted so that it blocks the current until the PFL is charged to peak voltage. At that point the core saturates, its permeability (and hence inductance) rapidly drops, and charge is quickly transferred through the inductor on a time that is much faster than the charge time. Our application follows the topology pioneered at LLNL [15] and in the Sandia RHEPP modulator [16]. Our circuit has only slightly

more than unity temporal gain to achieve the desired pulse shape. As the output voltage pulse is 400 nsec, the PFL must be charged in about 0.8 μsec

We have developed a new type of switch to meet these ultra fast switching requirements. This Laser Gated and Pumped Thyristor (LGPT) [17] is shown schematically in Figure 4. The device consists of a four-layer, solid-state switch that is optically triggered by two on-board diode laser arrays. The lasers flood the entire switch volume with photons to yield switching times of less than 100 nsec.

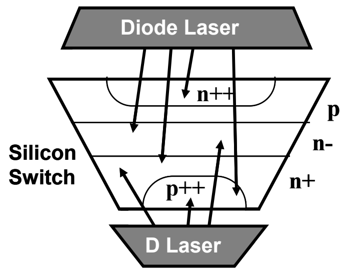

Figure 4: Schematic of the LGPT

The fast Marx application described above requires a fast closing switch that can operate at 16.4 kV, and can carry approximately 2.5 kA/cm^2 current density with a peak rate of rise of current of di/dt ≥ 10 kA/μsec/cm^2. We have developed both first and second generation versions of this switch, both in a square geometry with an area of 1 cm^2. The prototypes have survived several million-shot plus runs at 5 Hz, hold off the required design voltage, and have a current rate of rise of 88 kA/μsec/cm^2 and a current density of 14.7 kA/cm^2. This exceeds are our requirements. We are now repackaging the switch in an elongated geometry to realize the extremely low inductance needed for the fast Marx. Details of the switch and next generation package are given in [18].

Equally important for durability are the prime energy stores. We built a test bed to perform deep cycle tests of candidate capacitor technologies. The test bed allowed us to simultaneously evaluate two banks of 16 capacitors each. One set of capacitors had a storage density of 0.3 J/cm^3, the other 0.015 J/cm^2. Both systems held up with no failures for over 5 x 10^8 shots, running at 55 Hz. We terminated the test, not for technical reasons, but because we couldn't find anyone to sit next to the bank any longer.

Our first test of the advanced pulsed power architecture shown in Figure 3 will be carried out on the Electra Pre-amplifier [19]. This small e-beam system (175 kV, 85 kA, 40 nsec) will provide the laser input to the main amplifier, and it will be used to demonstrate the new technology. The system is shown in Figure 5. Currently the system uses a gas switched Marx, but otherwise is identical to the advanced pulsed power architecture. It can run for 100,000 shots and has very low jitter: less than 850 psec (1 σ) over 30,000 shots. The system has been run in an e-beam mode and is anticipated to run as a laser oscillator by the end of CY 2005. It will be retrofitted with a solid state Marx as soon as the new switch topology is ready for prime time. Further details on this system can be found in the references [20, 21].

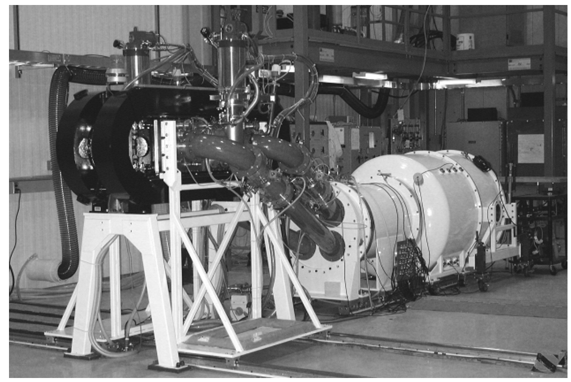

Figure 5: Electra Pre-Amplifier

C. Cathode development

The electron beam current must rise and fall quickly and be spatially and temporally uniform. Our work has concentrated on cold (field emission) cathodes owing to their simplicity, robustness, low cost, practically zero power consumption, ability to operate at ambient temperatures, and relatively modest vacuums requirements (10^{-4} Torr). While we have evaluated a number of cathodes [22], the most promising approach is to place a ceramic honeycomb structure in front of the emitter surface [23]. The ceramic improves the uniformity, decreases the rise and fall times, reduces the post shot evolved gas, and extends the lifetime of every cathode we have evaluated. The ceramic is made of cordierite, is 5 cm thick, and composed of close packed square capillaries, with a pore density of 300 ppi. The ceramic is situated such that one surface is 2 mm from the emitter surface, and the other defines the A-K gap. There are three underlying mechanism for the improvements: 1) The close proximity of the relatively high dielectric constant ceramic (ε = 6.3) reduces the localized reduction in electric field caused when one part of the emitter produces electrons. 2) The capillaries provide a plentiful source of secondary electrons. These secondaries quickly (less than 1 nsec) generate a plasma that electrically connects the emitter/ceramic gap. Thus the primary source of beam electrons comes from the inside of the capillary wall, and not explosive emission from the cathode material itself. This should significantly reduce erosion from the cathode with a concomitant increase in lifetime. 3) The large surface area of the capillaries absorbs gasses produced by the cathode and hence limits the amount of material that is released. Coating the inside of the ceramic with gamma alumina, which acts like a

reactive sponge to absorb residual gases, showed even further decreases in the post shot diode pressure rise.
Results from the "ceramic honeycomb" cathode are shown in Figure 5. Note the ceramic decreases the power rise time (in these shots the observed rise was actually diagnostic limited), decreases the power fall time, and produces a flatter power pulse. In addition, the diode pressure after the shot was reduced about five fold. In the case of the carbon fiber cathode, the RMS non-uniformity of the electron beam dropped from 14.8% to 4.6%. Further details can be found in the references [23].

We recently realized similar improvements with a different electron beam source with the similar voltage and current density (400 kV, 30 A/cm^2) but smaller cathode area (14 cm dia) and a longer pulse length (500 nsec, vs 140 nsec) [24]. The latter suggests this arrangement will scale to longer pulse systems.

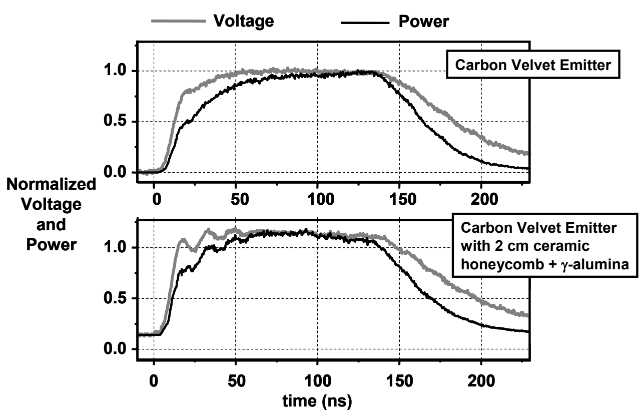

Figure 5. Comparison of power and voltage waveforms without (upper) and with (lower) the ceramic honeycomb placed in front of the emitter.

D. E-beam physics

Large area low impedance electron beams are subject to a "transit time instability." This instability was observed with experiments on the Nike 60 cm amplifier and successfully modeled [25] with a particle-in-cell code. The instability imparts an axial velocity spread to the electron beam, which lowers the energy transfer efficiency into the laser gas. The modeling showed the instability is unaffected by the magnetic field strength: It was varied between 1 and 100 kG with no effect. (The nominal field in the experiments is 2 kG.) The modeling also showed that slotting the electron beam cathode and loading the slots with microwave absorbing material can mitigate this instability. The slot width, depth, and pitch are precisely chosen so the phase velocity of the wave associated with the instability is close to zero. This concept has been demonstrated on the Nike laser [26]. The loaded slots reduce the amplitude of the instability can be reduced by a factor of 40,000. In effect the instability is eliminated.

E. Hibachi Development

The hibachi holds the pressure foil that isolates the laser gas from the vacuum region of the electron beam diode. Typically the hibachi consists of a series of parallel ribs that support the foil. An example of a standard hibachi designs is shown in the upper half of Figure 6. The rib structure supports the pressure foil on one side, and an anode foil on the other side, i.e facing the electron beam. The electron beam is emitted from a monolithic cathode. The electron energy deposition efficiency was only about 35-40% with this arrangement [27]. This efficiency is defined as the ratio of the energy deposited in the laser gas divided by the electrical energy in the diode. For these purposes we only consider the energy deposition during the 100 nsec flat top portion of the electron beam pulse.

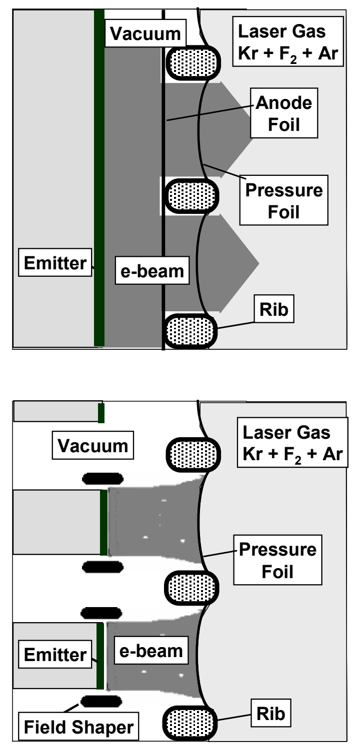

Figure 6: Upper: Conventional hibachi configuration. Lower: High energy deposition hibachi configuration. The electron beam is shown as an LSP simulation.

We have developed a hibachi concept that demonstrates energy deposition transmission efficiency of > 73% on Electra [28]. Efficiencies of > 81 % are expected in a full sized system running at 1,000 keV. The concept is shown in the lower half of Figure 12. The high transmission efficiency was achieved with two innovations: 1) Eliminating the anode foil that is customarily placed on the diode side of the hibachi structure, and 2) Patterning the electron emitter into strips so the beam "misses" the hibachi ribs. While conceptually simple these are difficult in practice: The individual beam strips spread while due to the highly non-uniform electric fields caused by eliminating the anode foil, and they rotate due to the

beam's interaction with the applied magnetic field. We compensate for these by narrowing the emitters and "counter-rotating" them so the beam strips propagate parallel to the ribs when they get to the hibachi. Note that slotting the cathode into strips also eliminates the "transit time" instability as described above.

While the topology of the strips can be empirically determined on Electra, this does not give us the predictive capability needed to design larger systems. This is a rather complex phenomenon and requires a full 3-D PIC simulation of the exact experimental geometry, including the rib structure, laser gas, and magnetic field. This was achieved with the Large Scale Plasma (LSP) code developed by MRC, Albuquerque. The simulations accurately predict both the cathode counter rotation angle and the energy deposition efficiency [29]. The electron beam depicted in the lower half of Figure 6 is an LSP simulation of a beam "strip". The field shapers in the figure reduce the current density enhancement that would normally occur at the edge of an electron beam [30].

F. KrF Physics/Laser Operation

Electra has been operated as an oscillator [31] . The laser cell is 30 cm wide (between pressure foils) by 30 cm high, by 100 cm long (along the laser axis). The laser resonator was created by adding a flat 98.5% reflecting rear mirror and an 8% reflecting output coupler. The required output coupler reflectivity was determined using the well established Rigrod formalism, and the small signal gain has been measured to be 6.0%/cm with a saturation intensity of 6 MW/cm^2 [32]. The laser behavior of Electra has been accurately modeled with Orestes, which is a first principals KrF physics code and not to be confused with the brother of the same name [33]. Orestes includes the electron deposition, plasma chemistry, laser transport and amplified spontaneous emission (ASE). The code follows over 22 species, 130 reactions, two excited electronic states of KrF*, and 53 vibrational levels. The code accounts for the e-beam input, laser input, plasma thermal and internal energies, the Amplified Spontaneous Emission (ASE), and the laser output. Orestes has accurately predicted the laser output of several different KrF laser systems over a wide range of conditions. Figure 7 compares the predictions of Electra with the experimental results.

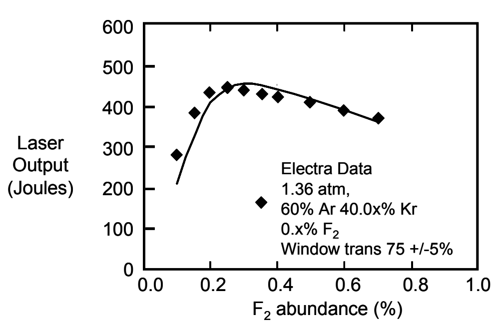

Figure 7: Comparison of Electra data and Orestes Code

Further details on Orestes, and comparison with the Electra experiments can be found in references [32, 34].

Of great importance is the intrinsic efficiency of the KrF laser. This is defined as the ratio of the KrF laser energy out, divided by the electron beam energy deposited into the gas during the flat portion of the power pulse. The latter figure must include the energy lost by radiation and the laser itself. Figure 8, below, shows the intrinsic efficiency in the oscillator mode is around 10%:

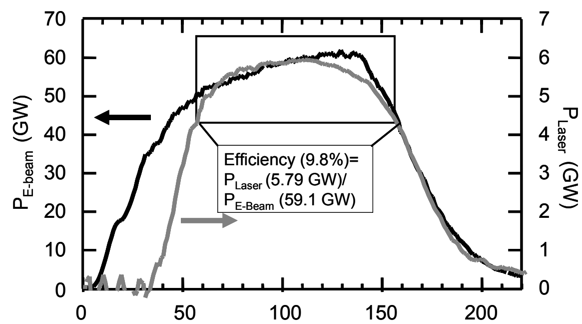

Figure 8: Laser output vs. electron beam input powers

In this case, the laser energy was 730 Joules. When running as an amplifier, without an output coupler and higher quality windows, we expect the intrinsic efficiency should be on the order of 12%.

G. Overall KrF Laser System Efficiency

Based on our current research, we project that the overall wall plug efficiency for an IFE sized KrF system will be greater than the 7.0% requirement in Table I. The breakdown is shown in Table II:

Table II: Projected efficiency for a large KrF system

Component	Basis	Efficiency
Pulsed Power	Advanced Switch	85%
Hibachi	No Anode, Pattern Beam	81%
KrF intrinsic	Electra Experiments	12%
Optics to target	Estimate	95%
Ancillaries	Pumps, recirculator	95%
	Total	**7.5%**

This table should be considered provisional, and future research will refine these projections.

H. Repetition Rate Issues

The key to long run durations is thermal management of the hibachi foil. We estimate we need to keep the SS-304 foil below ~300 °C for long lived operation. We are developing three different techniques to cool the foil:

1. Deflecting the laser gas, either permanently or between shots. This is the only technique we have fielded in a full scale hibachi to date [35].

2. Using a water mist aerosol between an anode foil and the pressure foil. This has the drawback of decreasing the system efficiency somewhat, but has proven to keep a Ti foil below 150 °C at 5 Hz in small scale tests [36].
3. Thermal conduction through the ribs. This requires advanced high thermal conductivity, high strength materials, and relatively close rib spacing.

Table III gives the operating modes to date for Electra. We used either a monolithic cathode, in which the beam hits the hibachi ribs, or a strip cathode, in which the beam misses them. The latter gives higher performance, as one would expect. The foil temperatures are estimated from reference [35]

Table III: Operating Modes for Electra[1]

Rep-Rate	Cathode	Laser Energy/ pulse (J)	Foil Temp (°C)	Duration (shots)
5 Hz	Mono	400	410	500
1 Hz	Strip	700	300	400
1 Hz	Mono	300	230	10,000

We believe we can continuously run for very long times at 1 Hz. But we have only operated for relatively short (~ 500 shot) runs at 5 Hz so far. We may achieve increased longevity at the higher rep rates by further refinement on the gas deflection technique. For example adding helium to the laser gas has been proven to lower the foil temperature [35]. In any event, our calculations show that either conduction cooling or mist cooling can get the foil temperature into a reasonable range at the higher rep-rates. These can be run in conjunction with gas deflection for more enhanced cooling.

In all of these cases the laser performance has been remarkably consistent. Figure 9 shows overlaid photo diode pulses measuring the laser output for the 10,000 shot 1 Hz run

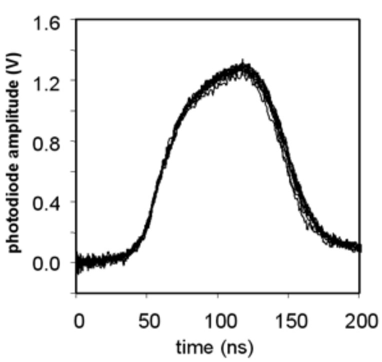

Figure 9: Overlaid photodiode traces for every 1000th shot of the 10,000 shot run.

[1] the difference in laser energy with the monolithic cathode is due to variations in the window transmission

VI. NEXT GENERATION SYSTEM

As discussed in the beginning of Section III, a full scale beam line for a fusion power plant would produce about 40 kJ of laser light. It is preferable to have a parallel array of pulsed power systems driving the electron beams, rather than a single one. This is to minimize thermal issues, allow for manageable systems, and to minimize damage from fault modes. Accordingly, we are presently evaluating a large amplifier that uses segmented cathodes. The laser gas would be pumped by an array of electron beams, with each beam powered by its own pulsed power system of the designs shown in Figure 3. Each cathode would be in the range of 50 cm wide by 100 cm high, and thus be smaller than the one used in Nike. The characteristic dimension of the optical aperture would be on the order of 100 cm or less, which is comparable to that of existing facilities.

V. SUMMARY

The Electra laser is nearing its goals of developing the KrF laser technologies that can meet the requirements for fusion energy. Advances in pulsed power, electron beam propagation, hibachi design and KrF kinetics lead to a predicted overall efficiency which should meet the 7% efficiency goal. Electra has operated as a laser oscillator for 10,000 shots at 1 Hz, and 500 shot at 5 Hz, with no degradation in output. The technologies that have been developed scale to a full size system.

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VI. REFERENCES

[1]. J.D. Sethian, et al, “Fusion Energy Research With Lasers, Direct Drive Targets, and Dry Wall Chambers,” Nucl. Fusion 43, pp1693–1709 (2003).
[2]. J.D. Sethian, et al, “Electron Beam Pumped Krypton Fluoride Lasers For Fusion Energy” Proc IEEE, 92, pp 1043-1056 (2004).
[3]. J.L. Giuliani, et al, “Ar-Xe Laser Experiments on the Electra Rep-Rated Electron Beam Generator”, 2004 IEEE International Conference on Plasma Science, June 28-July 1, 2004, Baltimore, MD, P 447 (2004).
[4]. N. G. Basov, et al, "60 J quasistationary electroionization laser on Xe atomic metastables", IEEE Journal of Quantum Electronics, Vol. QE-21, pp. 1756-1760 (1985).
[5]. V. N Smiley, “Review of high power excimer lasers” SPIE Volume on High Power Gas Lasers, pp 1225, 2, (1990).
[6]. Okuda, et al, Applied Physics B-Lasers and Optics 75, 623 (2001).

[7]. E. Divall, et al, Journal of Modern Optics 43, 1025 (1996).
[8]. S E Bodner, et al, "High gain direct drive target design for laser fusion," Physics of Plasmas 7, 2298-2301 (2000).
[9]. D. Colombant, et al, "Effect of radiation on direct drive laser fusion targets," Physics of Plasmas 7, pp 2046-2054 (2000).
[10]. A.J. Schmitt, et al, , "Large-Scale High-Resolution Simulations Of High Gain Direct-Drive Inertial Confinement Fusion Targets" Phys. Plasmas 11(5), 2716-2722 (2004).
[11]. V. Sviatoslavsky, et al, "A KrF Laser driven inertial confinement fusion reactor 'SOMBRERO'," Fusion Technology 21, 1470 (1992)
[12]. S. P. Obenschain, et al, "The Nike KrF laser facility: Performance and Initial Target Experiments," Physics of Plasmas 3, 2098 (1996).
[13]. J. D. Sethian, et al, "Pulsed power for a rep rate electron beam pumped KrF laser", IEEE Transactions on Plasma Science 28, 1333 (2000).
[14]. W.S. Melville, "The Use of Saturable Reactors as Discharge Devices for Pulse Generators," Proc. IEE, (London) Vol.98, Part 3 (Radio and Communication), No. 53, p.185 (1951)
[15]. D.L. Birx, et al, "Experiments in magnetic switching," Proc. Third IEEE Pulsed Power Conference, p 226 (1981).
[16]. L.X Schneider, et al, "Repetitive high energy pulsed power technology development," Proc, 14th Int Conf on Accelerators in Industry & Research, Denton TX, Nov 6-9 (1996).
[17]. D. Weidenheimer, et al, "Advanced pulsed power concept and component development for KrF laser IFE" to be published in the Proceedings of the IEEE Power Modulator Conference, Hollywood, CA, June 31-July 2, 2002 (IEEE Piscataway, NJ).
[18]. D. Weidenheimer, et al, "Laser Gated and Pumped Thyristor (LGPT) Scale-Up for the Electra Advanced Pulsed Power Technology Demonstrator', To be published in the Digest of Technical Papers, 15th IEEE Pulsed Power Conference, Monterey, CA. June 13-17, 2005.
[19]. D. Morton, et al, "Pulsed Power Design for a Small, Repetitively Pulsed, Electron Beam Pumped KrF Laser," Digest of Technical Papers, 14th IEEE International Pulsed Power Conference, Dallas TX June 15-18, 2003 pp 551-554.
[20]. D. Morton, et al, "Performance of an Advanced Repetitively Pulsed Electron Beam Pumped KrF Laser Driverl" To be published in the Digest of Technical Papers, 15th IEEE Pulsed Power Conference, Monterey, CA. June 13-17, 2005.
[21]. M.C. Myers, et al, "Electra Pre-Amplifier: a Repetitively Pulsed, Electron Beam Pumped, Krypton Fluoride Laser" To be published in the Digest of Technical Papers, 15th IEEE Pulsed Power Conference, Monterey, CA. June 13-17, 2005.
[22]. M.C. Myers, et al, "Development of a durable, large area cathode for repetitive, uniform electron beam generation," Digest of Technical Papers, IEEE Pulsed Power Conference, Las Vegas, Nevada, June 17-22, 2001. IEEE, NY pp 710 -713, (2001).
[23]. M. Friedman, et al, "Emission Of An Intense Large Area Electron Beam From A Slab Of Porous Dielectric," Journal of Applied Physics, 96, pp 7714- 7722, (2004).
[24]. J. Pasour, Private communication
[25]. M. Friedman, et al, "Stability of large area electron beam diodes," App Physics Letters 77, pp 1053- 1055, (2000)
[26]. M. Friedman, et al, "Initiation and Prevention of the Transit-Time Instability in Large-Area Electron-Beam Diodes," Journal of Appl. Physics, 95, pp 2797-2799, (2004).
[27]. J.D. Sethian, et al, "Large Area Electron Beam Pumped Krypton Fluoride Laser Amplifier," Rev Sci Instrum, 68, 2357 (1997).
[28]. F. Hegeler, et al. "Efficient Electron Beam Deposition in the Gas Cell of the Electra laser", Physics of Plasmas, 11, pp 5010-5021 (2004).
[29]. D. V. Rose, et al, "Numerical modeling of large-area electron-beam diodes for KrF lasers," Journal Appl Phys, 94, pp 5343-5349, (2003).
[30]. F. Hegeler, et al, "Reduction of Edge Emission in Electron Beam Diodes," Physics of Plasmas, 9, pp 4309-4315, (2002).
[31]. M.F.Wolford, et al, Electra: Repetitively Pulsed, 500J, 100 nsec, KrF Oscillator, Applied Physics Letters, 84, pp 326-328.
[32]. M.F. Wolford, et al, "High Yield Rep-Rate Operation of Electra, an Electron Beam Pumped KrF Laser," 2005 Conference on Lasers and Electro Optics, Paper JFB4, Baltimore, MD 2005.
[33]. Sophocles, "Electra", 410 BC
[34]. J.L. Giuliani, et al, "Orestes: A kinetics model for electron beam pumped KrF lasers," Presented at the Third International Fusion Science and Applications Conference, Monterey CA, Sep 8-12, 2003. Paper Wpo4.31. To be published in Fusion Science and Technology.
[35]. F. Hegeler, et al, "Thermal Loading of Thin Metal Foils Used as Electron Beam Windows for a KrF Laser," To be published in the Digest of Technical Papers, 15th IEEE Pulsed Power Conference, Monterey, CA. June 13-17, 2005.
[36]. S. Abdel Kahlik et al,"Mist Cooled Hibachi for KrF Lasers", presented at the 10th High Average Power Laser Program Workshop, 27-28 October 2004, Princeton Plasma Physics Laboratory, Princeton, NJ. See http://aries.ucsd.edu/HAPL/MEETINGS/0410-HAPL/abdel-khalik.pdf.